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Lessons Learned from Existing Projects on Shoaling in Harbors and Navigation Channels

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PURPOSE. Over the past few decades, several attempts have been made to reduce sedimentation in harbors and navigation channels. The National Research Council (1987) appointed a committee that produced a report on regional sedimentation control to reduce maintenance dredging of navigational facilities in estuaries. Wicker (1965) described fundamentals of tidal hydraulics related to estuarine shoaling. McCartney et al. (1991) published lessons learned on estuary waterways projects studied by the US Army Corps of Engineers, and by the Committee on Tidal Hydraulics. This Coastal and Hydraulics Engineering Technical Note (CHETN), which is more comprehensive than McCartney et al. (1991), draws general conclusions and offers updated lessons learned that cover an additional 10 years of experience.

Many of the mistakes made in the past have been very expensive and sometimes irreversible. The objective of this CHETN is to provide information on lessons learned from past projects so as to avoid similar mistakes in future projects.

INTRODUCTION. Siltation of ports and navigation channels is a serious problem at several ports in the United States as well as in many other countries in the world. Data on quantities and cost of annual maintenance dredging in the United States are published on an Internet Web page by the Navigation Data Center of the US Army Corps of Engineers (2002). Data for the years 1995 through 2000 show that the average annual maintenance dredging in Federal navigation projects was 176 million cu m (230 million cu yd) at a cost of about $500 million. This represented 86% of the total dredging volume and 75% of the total dredging costs per year for the US Army Corps of Engineers. In addition, maintenance dredging is also done at private marinas, basins, and small-boat harbors. Keeping the rate of shoaling to a minimum is a major consideration for site selection and harbor design. The most obvious reason for the need to reduce shoaling is to reduce recurring costs of dredging. Other reasons include navigation problems resulting from reduced project depths and environmental problems caused by maintenance dredging operations. Oftentimes, shoaling increases as a result of the implementation of harbor expansion schemes or other unforeseen causes such that it becomes essential to take remedial measures to reduce shoaling after the harbor becomes operational.

SEDIMENT PROCESSES AND HUMAN INTERFERENCE. Sediment occurs in the natural environment on banks and beds and also in suspension in the water column. Sediment may become suspended in water when forces of waves, wind, and current dislodge it from the bed. Suspended sediment deposits when the available energy is less that that needed to keep it suspended against the force of gravity.

There are a few similarities and several significant differences in the depositional processes of noncohesive and cohesive sediments. The movement of fine sediment in an estuary can be

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considered as a cycle of four processes: (1) erosion, (2) transport in suspension, (3) deposition, and (4) bed consolidation. Since each of these is a complex and not-well-defined function of both the tidal flow properties and sediment characteristics, empirical expressions have to be used to describe the mathematical relationship. Laboratory and field experiments are necessary to determine the constants in these expressions. Wicker and Eaton (1965) have described sedimentation in tidal waterways. Mehta (1986) has described the estuarine transport processes in detail.

The natural sedimentary processes undergo changes resulting from human interference. Several measures can be taken to reduce shoaling in harbors and navigation channels. These are based on past experience, results of physical or numerical model studies, or analysis of field data. Such measures may be considered as successful if they met the intended objective, or they may be considered as a failure if the intended objectives were not met. Either way, such actions provide valuable lessons to the design and practicing engineers. The most valuable lessons are learned from the designed projects that were constructed and monitored over a period of time to permit meaningful evaluation. A little less valuable are the cases where laboratory and field studies were conducted on the proposed actions, but the projects were either not constructed or not monitored.

This CHETN offers examples of success and failure of a variety of actions proposed or taken in the context of channel and harbor shoaling. Examples of specific projects in the United States and elsewhere are given under each type of action. It is interesting to note that measures that have been highly successful at one project may not be useful at some other project due to different site conditions, environmental parameters, availability of construction materials, costs, and so on. Some projects require adoption of multiple measures to overcome the shoaling problem. This technical note describes lessons learned from design and structural and operational measures undertaken at several projects for reducing shoaling in harbors and navigation channels. Parchure and Teeter (2002 [rev. 2003]) give details and maps of several projects.

Jetties at Tidal Inlets/Estuary Mouths. Jetties are often constructed at the mouth of tidal inlets and estuaries to stabilize their location with reference to the shoreline, such as Green Harbor, MA (Weishar and Aubrey 1988). Such jetties cause substantial accretion on the updrift side and erosion on the downdrift side when the shoreline has littoral drift. Permeable jetties and jetties with crest elevations that are low relative to the adjacent beach can influence erosion of adjacent beach and shoaling of the inlet channel. One or two jetties may be provided at the entrance to tidal inlets to stabilize the inlet, navigation channel, or the outer shoal. Usually, the construction of two jetties at coastal entrances will have one of three configurations: (1) both straight and parallel, (2) both curved and parallel, or (3) non-parallel, arrowhead-shaped. General guidance can be deduced based on earlier studies on the behavior of these jetties.

Case studies.

- New jetty at Ocean City Inlet, MD (Rosati and Kraus 1999). A new jetty had to be constructed 10 m south of the existing jetty with a higher crest elevation. An impermeable core was provided, and three headland breakwaters were constructed.
- Southwest Pass, Mississippi River (Simmons and Rhodes 1965). Modifications included relocating the bar channel and reduction of the channel width.

Lessons learned.

- Properly designed jetties at tidal inlet or estuary mouth are effective in arresting migration of an inlet along a shoreline.
- If such structures are constructed on a shoreline with a substantial littoral sediment transport, deposition of sediment takes place on the updrift side and erosion of beach occurs on the downdrift side.
- Jetties at inlet mouths are often not effective in preventing sediment deposition in the navigation channel unless they are very long, on the order of kilometers.
- Arrowhead jetties tend to cause shoaling because the ebb flow is not confined enough to produce nondepositional velocities inside the widest part between the jetties. This can also allow or cause channel migration (e.g., Columbia River, Galveston Bay).
- Parallel straight jetties usually confine ebb flow resulting in flushing sediment out. This may, however, result in formation of an ebb delta.
- Curved parallel jetties such as those provided at the Umpqua River entrance, can be designed to produce nondepositional velocities; however, flow concentration may take place on the outside curve resulting in undermining of the jetty. Also, curved alignment may be difficult to navigate when the channel depth and width are not uniform.
- Jetties should be extended beyond the littoral zone to minimize shoaling problems. Preferably, they should be extended to an offshore depth contour greater than the depth of the navigation channel (e.g., Rogue River, OR [Bottin 1982]). Sand bypassing arrangements can be made to prevent erosion of downdrift side.
- The outer end of jetties should be submerged at high tide unless the jetties are meant for wave protection. This reduces the flood tide potential to carry littoral material into the channel (e.g., Grays Harbor, WA).
- Reducing jetty spacing to the extent permissible for safe navigation and avoiding scouring velocities reduces shoaling (e.g., Tillamook Bay, OR).
- Channels migrate toward the jetty when a single jetty is provided at the entrance. This may cause scouring of the jetty foundation (e.g., Tillamook Bay, OR).
- Adjustment of channel side slopes requires several years and continues to be a source of sediment into the navigation channel (e.g., Columbia River mouth, Matagorda Ship Channel). Reaching equilibrium for the jetty system may take a century or more (e.g., Galveston Bay entrance).

Channel Realignment. Guidelines are available on the design of navigation channels in terms of width and depth for different types of vessels. Maneuvering characteristics of large vessels such as oil tankers, bulk carriers, container ships, and aircraft carriers must be taken into account when designing curvatures along a channel. Attempts are made to locate a channel in naturally deep areas to minimize the initial and maintenance dredging requirements. Most of the sites experience change due to continuous sedimentary processes such as shifting sand bars. Realignment of a channel becomes necessary if the existing channel experiences excessive sedimentation, which can be reduced by relocating the channel to the naturally available nearby deep water. Two problems arise; first, the nearby deep water may not be stationary and second, it is very elaborate and expensive to relocate all the navigation markers and buoys on the new channel and inform the international maritime community that may be using them.

Case studies.

- Red River Waterway, LA (Pinkard 1995). The Corps suggested realigning the channel throughout the project reach to eliminate problems of bank caving, overcome navigational difficulties, and reduce flood stages. The project was completed in 1994 and it has been reported that no maintenance dredging is required to keep the realignments open since then.
- Southwest Pass, Mississippi River (Simmons and Rhodes 1965). Modifications included realignment of the jetty channel.

Lessons learned.

- Providing cuts in meanders shortens the channel length, increases water-surface slope, increases flow velocities, reduces sediment deposition, and increases the drainage efficiency and thus reduces flood levels. However, this may not be an environmentally acceptable solution. It may also induce bank erosion.
- Realignment or relocation of an existing navigation channel from a shallow area to another nearby location to take advantage of locally available deep water is often beneficial in reducing dredging for channel maintenance.

Pilot Channel Construction. The pilot channel concept consists of excavating a pilot channel of smaller cross section than the desired section and allowing the natural erosive action of the river to erode the pilot channel to its ultimate section. The major advantage of this method of channel realignment is that the cost of channel excavation is greatly reduced. However, it is essential to leave sufficient time to allow the pilot channel to fully develop. The banks of such a channel are stable and contribution of sediment to shoaling from bank erosion is eliminated. Such field experience is valuable for making channel realignment at other places over long reaches of river.

Case studies.

- Red River, LA (Pinkard 1995).
- Mississippi River (Nickles et al. 1985).

Lessons learned.

- Construction of a pilot channel is a feasible option of channel realignment under favorable site conditions.
- The major advantage of this method is that the cost of channel excavation is greatly reduced. It is essential to leave sufficient time to allow the pilot channel to fully develop. The field experience gained from the construction of one pilot channel is valuable for affecting channel realignment at other locations on the same site. Construction of a pilot channel also helps in bank stabilization, thus avoiding sediment deposition in navigation channels.

River Diversion and Rediversion. When a natural stream is found to carry and dump a substantial amount of sediment in a harbor or navigation channel, the first thing that may be considered is to divert the river away from the area of interest. This action may or may not be effective, depending on site conditions. Hence, careful model studies and analysis of data are essential before taking any action.

Case studies.

- Charleston Harbor, SC (Committee on Tidal Hydraulics 1966, Patterson 1983, Teeter 1989). Diversion of large volumes of fresh water from Santee River to Copper River changed the Cooper River estuary from well-mixed to partially-mixed, and also increased the flood predominance. This increased the shoaling from 0.07 million cu m (0.1 million cu yd) a year before diversion to 7.6 million cu m (10 million cu yd) a year after the project was completed. Partial rediversion of fresh water back into Santee River brought annual shoaling down to about 4.6 million cu m (6 million cu yd).
- Savannah Harbor, GA (US Army Corps of Engineers 1961). The major source of shoaling material was the fresh water flowing through the harbor to the ocean. Model studies showed that river diversion would be successful in reducing shoaling, but this may create serious problems of pollution.
- Gastineau Channel, AK; Colorado River, TX; Mississippi River Gulf Outlet (McCartney et al. 1991). Providing a barrier dike to separate and divert sediment-carrying riverflow away from the navigation channel reduced maintenance dredging.
- Delaware Bay. Model studies showed that a decrease in freshwater flow due to construction or regulation of a dam upstream increased the length of penetration of salt water, resulting in a change in location of shoaling.

Lessons learned.

- Diversion of large amounts of river water may cause a change in the mixing characteristics and sedimentary processes of an estuary, which may result in a substantial deposition of suspended sediment.
- By rediverting river water back to the original condition, it may be possible to reverse the estuarine sedimentary processes.
- Separation of river flow from the harbor entrance can reduce shoaling of navigation channels (e.g., Mission Bay, CA).

Current Deflector Wall. Eddy currents often cause shoaling. In such cases, dredging the shoal is not always cost-effective. A new method developed in Germany uses an innovative low training structure called the current deflector wall (CDW) to eliminate the eddy currents. A CDW is a fixed vertical-walled structure with a curved deflector wall that extends through the full depth of water. A rounded vertical-walled addition to the existing upstream entrance corner will usually be required to complement the CDW. The current deflector structure modifies flow patterns in such a way that eddies with an adverse effect on navigability and side channel sedimentation rates are diminished.

Case studies.

- Hamburg Port, Germany (Alexander 1993). The current deflector wall eliminated eddy formation, improved navigation, and resulted in a 41% reduction in shoaling.
- Antwerp Harbor, Belgium (Pettweis and Sas 1999). Results of numerical model studies on sedimentation of mud in the access channels to the harbor showed that a current deflector wall was not an acceptable solution at Antwerp because of salinity gradients which are absent at the Hamburg Harbor. Hofland et al. (2001) reported in a subsequent study that a CDW can be effective under density-induced currents; however, site-specific studies are essential.

Lessons learned.

- A current deflector wall (CDW) has been successful in reducing siltation at Hamburg Harbor, Germany, by 41%.
- This option was not considered applicable at Antwerp, Belgium, because Antwerp has salinity gradients which are absent at the Hamburg Harbor.
- A CDW can be effective under density-induced currents; however, site-specific studies are essential.

Channel Closure. A small tributary, drainage canal, or creek may be bringing a substantial quantity of sediment from aquatic or overland source into the navigable area, thus contributing to the maintenance dredging quantity. If the outlet of this source is beyond the tidal limit of an estuary and if the quantity of fresh water is small and intermittent, it may be feasible to close the channel and reduce sediment input to the dredging quantity.

Case study.

- Delaware River Channel (Bobb 1967). One of the conclusions of a hydraulic model study was that a significant reduction in shoaling may be achieved by complete closure of the Tinicum Island back channel.

Lesson learned.

- If a tributary channel has been established to be a major source of sediment, closure of such a channel and diverting it elsewhere may be an effective solution, provided the diversion along alternative route is technically, economically, and environmentally feasible.

Entrance Closure. The ocean can be the main source of sediment getting in an inlet, either as bed load or suspended load. If the harbor located inside is small, meant only for recreational or fishing vessels, arrangements for intermittent closure of the inlet to arrest entry of sediment may be feasible. Caution needs to be exercised to prevent shoaling outside and choking of the inlet during the duration of the closure.

Case study.

- Dillingham Harbor, AK (Everts 1976). The most unusual feature planned for the Dillingham harbor was construction of a steel closure structure in the entrance channel; however, it was not constructed because of practical difficulties.

Lessons learned.

- This option works only for small channels where temporary closure and periodic reopening by means of a movable structure is feasible.
- Also this option works only when the sediment input is from an outside source such as the ocean.
- Sometimes, a barrier serves a dual purpose of storm surge protection and arresting sediment.

Sediment Traps. Catching sediment before it enters the sensitive area is one of the most effective methods for management of sediment deposition. Under favorable conditions of site and climate, this can be achieved by providing a sediment trap at a carefully selected location. Sediment traps do not catch all the sediment moving in the area. Hence, dredging cannot be completely avoided but the frequency and quantity of dredging can be significantly reduced. This increases the efficiency of use of harbor facilities and results in significant cost savings on maintenance dredging. The sediment trap itself must be emptied periodically to keep it functional. Although the volume to be dredged from the trap usually offsets any reduction in project shoaling, there can still be benefits, including: (1) no disruption of navigation by shoaling in the project, (2) reduction of overall dredging costs (usually) by less frequent dredging, and (3) the fact that the trap can be intentionally located close to dredged material disposal areas, etc. Sediment traps are not very common because they can be effective only at highly selective locations and cannot be provided as a general solution to channel sedimentation problems. Physical or numerical model studies are very useful in designing sediment traps.

Case studies.

- Delaware River Channel, Marcus Hook – Schuylkill River reach (Bobb 1967). A fixed-bed hydraulic model was used to qualitatively assess the relative merits of several proposals consisting of 17 plans. One of the conclusions of the study was that a combination of three sediment traps and a deepened portion of Marcus Hook anchorage would materially reduce navigation channel maintenance from the Philadelphia Navy Yard to Marcus Hook.
- Delaware City Channel (Bobb 1965). The Tidewater Oil Company, Delaware Refinery, at Delaware City explored the possibility of reducing shoaling at their facility. Six plans were developed consisting of dikes and two locations of a sand trap. Results of investigations showed that all the plans tested had an adverse effect on total shoaling in the company channels. If the plans were implemented, total shoaling was expected to increase by amounts varying between about 38,000 and 363,000 cu m (50,000 and 475,000 cu yd) per year depending on the plan.
- Rollover Pass, TX (Parchure et al. 2000). Based on a desktop study a sediment trap was designed on the south side of the Gulf Intracoastal Waterway (GIWW). Field data on its functioning will be available after the trap is constructed.
- Visakhapatnam Harbor, India (Parchure 1978). Based on the experience of a functioning sediment trap for the existing harbor, a new sediment trap was designed for the new outer harbor. This trap has been functioning successfully since its construction in the 1970s.
- Channel Islands Harbor, CA (Hobson 1982). The Channel Islands sediment trap has functioned well as designed by trapping the bulk of littoral drift sediment.
- Carolina Beach, NC (Jarrett 1988). The sediment trap in Carolina Beach Inlet has functioned fairly well but was located too close to the main flow through the inlet to be completely effective. Relocation of the sediment trap seaward of, and away from, the main channel should greatly enhance its overall sand trapping ability.

Lessons learned.

- Sediment traps are not always successful in trapping sediments before they reach areas of interest. They function efficiently only when the sediment is funneled effectively towards the trap. The location of a sediment trap needs to be determined carefully for it to be efficient.
- The sediment trapping efficiency depends on the size and depth of the trap, mode of sediment transport (bed load or suspended load), and sediment particle size.
- Sand traps are efficient in catching bed-load transport consisting of sand. Larger and deeper sediment trap may be required for trapping suspended sediment.

Silt Curtain. A silt curtain offers a physical barrier to sediment entering the area of interest. However, it is seldom used because it is only partially effective and also hinders navigation.

Case studies.

- Mare Island Naval Shipyard (Bailard, Dellasipa, and Flor 1986). The silt curtains are pneumatically controlled for raising and lowering, and have shown great potential in reducing the Navy's maintenance dredging burden.
- Antwerp Harbor, Belgium (Pettweis and Sas 1999). Based on numerical model studies on sedimentation of mud in the access channels, it was concluded that a silt screen was not applicable for the site because of possible frequent damage by ships.

Lessons learned.

- Silt curtains may be effective in preventing siltation at a local spot such as a berth or a jetty.
- Their maintenance and periodic raising and lowering is often an expensive proposition.

Basin Geometry. The geometry of harbor basins needs to be designed so as to avoid areas of low flow and eddies because they can induce excessive sediment deposition. If such areas are noticed later, or if new harbor expansion is proposed, the shape of the harbor should be studied by a physical or numerical model to achieve avoidable sedimentation problems.

Case studies.

- Dillingham Harbor, AK (Everts 1976). Several layout plans were studied for an expanded harbor taking into account the maintenance difficulties and cost benefit considerations for each. None of the tested configurations maintained velocities sufficient to prevent the settling of 0.006-mm-size particles present in the tidal water at the site.
- McCartney et al. (1991) reported that increasing the dimensions of a harbor reduces velocity and induces deposition of suspended sediments (e.g., Brunswick Harbor, Delaware River).
- McCartney et al. (1991) recommended that harbors should be located on the outside of river bends because the inside of the bend has lower flow velocities and tends to shoal (e.g., Gold Beach Harbor; Rouge River, OR).

Lessons learned.

- Modifying basin geometry by means of structures such as dikes, breakwaters, or a new entrance may be effective in reducing channel siltation.
- Physical and/or numerical model studies are recommended in selecting the optimum options.

Half-Tide Harbors. Harbor shoaling is a significant problem when coastal waters are laden with suspended solids and the tidal range is high such as in Alaska. Under these circumstances, half-tide harbors are constructed as enclosed basins adjacent to, rather than within, navigable estuaries for use of small crafts. The unique feature of the half-tide harbor is a sill placed in the navigation channel at an elevation higher than the bottom of the harbor basin. When the tidal level is low, the sill retains water in the harbor for vessel floatation.

Case study.

- Dillingham Harbor, AK (Everts 1976, Smith 1984). This enclosed small-craft half-tide harbor has diurnal tidal range of 5 to 6 m and the suspended sediment concentration is on the order of 1,000 mg/L. The large tidal range precluded a channel and basin that provided access at all stages of tide. Hence, a rock sill was placed in the 15-m-wide creek channel with a top elevation of +2.1 m mean lower low water (mllw). The basin behind the sill was dredged to +0.6 m mllw, providing 1.5-m depth inside the basin at low tide for floatation of small vessels. This sill elevation allowed navigation access in and out of the harbor approximately 46% of the time.

Lessons learned.

- It is feasible to plan half tide harbors with a suitably designed sill at its entrance for use by small crafts.
- Siltation of harbor and damage to the sill crest need particular attention.

Breakwater Construction. Breakwaters are constructed mainly for providing protection against waves to permit safe entry and exit of vessels, and loading and unloading operations at berths. They are also provided for sediment management, which may include functioning as weirs for overflow of sediment, sand traps on the sheltered side, and a barrier for diverting sediment.

Case studies.

- Port Orford, OR (Chatham 1981). Model studies offered a solution to sedimentation problems caused by breakwater extension.
- Columbia River (McAnally 1983). Numerical model studies confirmed the optimum length of the jetty.
- Madras Harbor, India. Construction of breakwaters on a beach with significant littoral drift resulted in the creation of an extensive and wide beach on the south side called the Marina Beach. It also resulted in beach erosion on the north side of the navigation channel.

Lessons learned.

- Construction of a shore-connected breakwater to prevent entry of alongshore sediment transport may result in a temporary success. However, if such structures are constructed on a

shoreline with a substantial littoral sediment transport and no other measures are taken, deposition of sediment takes place on the updrift side and erosion of the beach occurs on the downdrift side.

- After filling of the updrift side, sediment starts bypassing the seaward end of the breakwater and at least some of it will deposit in the entrance channel.

Weir in Shore-Connected Breakwater. Navigation channels provided at sites with littoral drift are subjected to heavy shoaling. Jetties or breakwaters constructed at the entrance arrest sediment transport which may accumulate all the way to the top of the obstruction. Hence, a section near the shore is sometimes provided with an elevation lower than the rest of the structure to act as a weir to permit overflow of sediment. A sediment trap is provided on the lee side to collect the sediment which can then be bypassed to the beach on the other side of the entrance.

Case study.

- Murrell's Inlet, SC (Rosati and Kraus 1999). Results of a 9-year monitoring program indicated that the sediment tended to transport over and through the weir jetty; however, some of the sediment then bypassed the deposition basin and deposited in the navigation channel. It is likely that a sediment deflector wall (which was recommended but not constructed) would have retained sediment within the deposition basin.

Lesson learned.

- A weir on a shore-connected breakwater at its shore-end permits flow of sediment over the weir and deposition in a sediment trap on the other side. This can be an effective sediment management tool.

Agitation Dredging/Side-Cast Disposal. Agitation dredging consists of loosening the bed sediment and letting it transport away from the area of interest by the currents. Local devices such as hydraulic jets and vortex foil arrays can be used for this purpose. The method is applicable for keeping a small local structure such as a berth or jetty sediment free, and where the currents are strong enough to carry the sediment in suspension over large distance with little possibility of returning to the same site later. Agitation dredging can also be performed with a dredge equipped with a deflector plate behind the propeller. Prop wash is deflected to the bottom where it resuspends sediments deposited in the channel. Ambient currents remove the resuspended sediments away from the channel.

Side-cast disposal of dredged material consists of depositing the dredged sediment through a pipe on one or both sides of a navigation channel. Depending on the type of sediment, substantial sediment so disposed is likely to deposit back into the channel. The method is often employed where the dredging quantity is small and the currents are parallel to the channel.

Case study.

- Lower Mississippi River. Agitation dredging is conducted in certain reaches of the navigation channel in the lower Mississippi River and is found to be economical. At the mouth of Southwest Pass, however, it has been found that improper location of the discharge point can result in sediment quickly settling into a very strong saltwater density wedge and being transported immediately back into the navigation channel.

Lesson learned.

- Agitation dredging offers an urgent but temporary solution to sedimentation over small reaches.

Local Devices. A few devices have been evolved through laboratory and field research for offering solutions to sediment accumulation problem at local spots.

Case studies.

- Hydraulic jets consist of a series of horizontal, near-bottom water jets which are briefly activated during each ebb tidal cycle. The shear stress imposed by the jet discharge resuspends any recently deposited sediment, creating a fan-shaped scour pattern in front of each jet. Once suspended, the sediment is carried away from the berthing area by ebb tidal currents. Use of spatial scour jet arrays at the Mare Island Naval Shipyard has been validated through field tests and has shown great potential in reducing the Navy's maintenance dredging burden (Bailard et al. 1986).
- Vortex foil array (Bailard et al. 1986). A vortex foil array device was developed for reducing sedimentation at berthing and approach areas exposed to moderate currents. These arrays consist of a series of underwater foils similar in cross-section to airplane wings, which are moored about 0.3 m (1 ft) above the bottom by a short tether wire connected to a swivel and screw anchor. Each delta shaped foil is buoyant, with its lifting surface oriented either upward (a downwash foil) or downward (an upwash foil). Tidal currents flowing past each foil cause horseshoe-shaped vortices to be shed from the foil's trailing edge. The vortices are advected downstream by the current, enhancing the bottom shear stress and resuspending newly deposited sediments. Use of vortex foil arrays has been validated through field tests at the Mare Island Naval Shipyard and have shown great potential in reducing the Navy's maintenance dredging burden.
- Venting canal concept. This device developed by the Scripps Institution of Oceanography has been evaluated by the Navy for reducing sedimentation in the turning basin at Naval Station Mayport, FL. The concept involves constructing a shallow canal connecting the basin with the adjacent St. John's River. The canal would function by preferentially filling the turning basin with relatively sediment-free water entering the existing entrance channel. Bailard et al. (1986) have reported that use of the venting canal concept has been validated through field tests, and has shown great potential in reducing the Navy's maintenance dredging burden.

Lesson learned.

- The success of installation of local devices such as hydraulic jets, multiple foil arrays, and venting canals in reducing the sediment deposition problem is very much site-specific, and they are effective only for a small local area.

Advance Maintenance Dredging. Some sites do not permit dredging over certain times of the year when the adverse weather conditions make dredging operation risky or ineffective. The adverse climatic condition is often a high-energy event, which may cause heavy shoaling. Under such circumstances, the navigation channel is dredged in excess of the minimum navigational requirements. The excess depth is the allowance for anticipated siltation, which is based on field

experience or engineering estimates. Advance maintenance dredging is also used to reduce the frequency of dredging operations, which usually reduces annual costs and results in less frequent disruption to navigation.

Case study.

- Cochin Port, India (Gole et al. 1969). The channel is overdredged by as much as 2.1 m (7 ft) before the onset of monsoons in May. Fine sediments in the ocean fill this up with a fluffy fluid mud, which is removed after the weather permits.

Lessons learned.

- At certain sites where dredging is impossible during adverse weather conditions, advance maintenance dredging is perhaps the only option because dredging must be done only when the weather permits.
- The depth of advance maintenance dredging may be large, on the order of 2 m or more.

Channel Widening and Deepening. Channel widening and deepening is probably the most common reason for increased shoaling. The channel modifications are often needed to permit larger vessels with greater drafts or to make the existing channel safer for navigation. On the other hand, if strong currents are bringing sediment into the harbor basin, widening may reduce the currents and hence, shoaling.

Case studies.

- Cochin Port, India. Experiments conducted in a saline water model indicated that the salt-water wedge would move upstream and velocities in the outer channel would drop particularly at the bed as a result of deepening the channel from 9.7 to 13.7 m (32 to 45 ft). This would result in increasing the rate of siltation in the outer channel from the existing value of 1.5 million cu m (2 million cu yd) to an anticipated value of 3.8 million cu m (5 million cu yd) per year (Gole et al. 1969.)
- Kings Bay, GA. The USNavy decided to deepen the harbor at Kings Bay, GA, and build a naval submarine base to accommodate trident class submarines. The US Army Engineer Research and Development Center performed a hydrodynamic physical model study of the project. It was predicted that shoaling would increase to about 4.6 million cu m (6 million cu yd) per year from less than 0.76 million cu m (1 million cu yd) per year without the base. As the project progressed and as the base was constructed, it appeared that the shoaling was not going to increase to those levels. The modeling continued and it was determined that the armoring of the material was not adequately represented in the model. The revised estimate of shoaling was reduced to about 1.53 million cu m (2 million cu yd) per year. The current dredging rate is somewhat less than this.
- Savannah Harbor. Progressive increases in channel depth and length at Savannah Harbor resulted in greater penetration of the salinity wedge. The shoaling location moved upstream and the shoaling rate increased dramatically.
- McCartney et al. (1991) reported that expansions of harbor widths at Brunswick Harbor and Delaware River have reduced velocities and caused rapid shoaling.

Lessons learned.

- Deepening of estuarine navigation channels results in increased penetration of saltwater wedge further upstream. This results in an increased deposition of suspended sediment.
- Increasing width and depth of a navigation channel increases the quantity of sediment deposition.

Dikes. Dikes have been used at innumerable river projects over the past century all over the world for modifying flow pattern in rivers to offer a solution to a variety of sedimentation problems such as improvement in flow pattern, bank protection against erosion, sand bar stabilization, and channel shoaling. Dikes consist of several types such as kicker dikes, spur dikes, submerged wing dikes, curved longitudinal dikes, transverse dikes, etc.

Case studies.

- Movable bed model studies conducted on the sedimentation problems at Buck Island reach of the Mississippi River offered the following solutions (Nickles et al. 1985): (1) Rebuilding of dikes would restore the channel to its alignment prior to floods of 1973, and (2) Construction of vane dikes would realign the channel and reduce shoaling.
- A curved longitudinal dike and two transverse dikes were recommended to maintain a uniform channel width and thus avoid expansion of flow area and consequent shoaling of the channel at the Red River Waterway (Mueller, Maggio, and Pokrefke 1992).
- Hydraulic model studies for St. Louis Harbor showed that placement of a longitudinal dike will tend to reduce shoaling (Franco 1972).

Lesson learned.

- Dikes are effective in solving a variety of sedimentation problems, including reduction in channel shoaling provided they are carefully designed.

Multiple Options. Out of numerous options available for reducing siltation in harbors and navigation channels, more than one option may be needed at certain sites to achieve the desired economically feasible rate. Implementation of multiple options is often successful.

Case studies.

- Ninilchik Harbor, AK: Sediment trap, French drains, diversion dikes, entrance closure, and basin geometry (Everts 1976).
- Savannah Harbor, GA: Sediment traps, river water diversion (US Army Corps of Engineers 1961).
- Cattaraugus Creek Harbor, NY: Breakwater, basin geometry (Bottin and Chatham 1975).
- Hudson River Channel: Sediment basins, diversion dike, channel realignment, channel closure (Simmons and Bobb 1965).
- Sunny Point, NC: Hydraulic jets, redistribution of sediment (Holiday, Wutkowski, and Vallionus 1984).

Lesson learned.

- Adoption of multiple measures at a project site is often an effective way of reducing sedimentation of harbors and navigation channels. The options may include two or more of the following: sediment trap, diversion dikes, river water diversion, modification of basin geometry, channel realignment, installation of devices such as hydraulic jets and vortex foil arrays.

Construction of Harbor Facilities. Expansion of harbor facilities often includes construction of structures such as berths, jetties, turning circles, and basins.

Case study.

- McCartney et al. (1991) concluded that side channels, basins, and pier slips in estuaries can often be effective sediment traps, resulting in higher shoaling than at other places (e.g., New York Harbor, Cape Fear River, US Navy Military Ocean Terminal at Sunny Point). Piers may create eddies that increase shoaling (e.g., New York Harbor, San Francisco Bay).

Lessons learned.

- New berths and jetties need to be carefully designed in terms of their location and configuration so as to avoid excessive siltation.
- The berthing face should be aligned parallel to the current to permit flushing of sediment.

CONCLUSIONS. A large number of waterway engineering projects have been executed all over the world predominantly during the last century. These included construction of new harbors (coastal, estuarine, riverine, etc.), shore protection works, and modification and expansion of existing facilities. With only a few exceptions such as the Singapore Port, most harbors have to deal with the problem of sediment deposition and shoaling at the existing and new facilities. Several lessons are learned from the success and failure of many projects. The lessons learned are extremely important in planning and designing future projects. It is interesting to note that measures that may be successful at one site may not work at another site because of differing natural conditions or other restraints. On the other hand, certain experiences such as those of littoral drift problems are universally applicable. This technical note, which has summarized major lessons learned and offered examples of projects where they were learned, should serve as a good general reference for guidance regarding shoaling in harbors and navigation channels. References to this CHETN provide additional information on various projects.

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